CHAPTER 11

Reliability and Optimisation

CONTENTS

	Paragraphs
Introduction	1 - 2
Practical Considerations for Reliability	3 - 10
Practical Optimisation	11 - 12
Probabilistic Design and Analysis	13 - 23
Optimisation	24 - 39
Choice of Object Function	36 - 39

CHAPTER 11

Reliability and Optimisation

Introduction

1 At first sight reliability and optimisation may seem unlikely subjects to bracket together in the same chapter. Reliability is an attribute of a structure in the same way as weight and cost, although not as precisely measurable, while optimisation is a means of improving a particular attribute, for example minimising weight, at the expense of others but within acceptable constraints. However, as they both use analogous mathematical techniques and as they both are in the main *analytical* methods which can only be rigorously applied after an initial design of structure has been developed in some detail, it is convenient to discuss them together.

2 In each case, before any objective analysis is undertaken, there are a number of practical aspects which should be considered during the design synthesis stage, which should lead to a more reliable and perhaps more optimum structure. Indeed, such considerations are important even if it is not intended to carry out any formal numerical refinements to the design. This chapter will, therefore, start with the mathematical techniques which are available. However, note that as these techniques are still under development and are not yet of general use to the designer, only a brief overview is presented but with reference for deeper reading.

Practical Considerations for Reliability

3 Probably the first and most important parameters to be defined are the expected life of the hull, the expected fraction of time at sea and the frequency during that life with which it will be possible to undertake structural surveys and repairs. For a merchant ship the life will be the subject of commercial calculation, that is the financial rate of return in relation to the capital cost and its depreciation. A more reliable hull will cost more but will last longer and can be paid for over a longer period out of revenue, as long as the trade for which the ship is designed remains profitable. Beyond that point the hull will be sold downmarket or scrapped to realise its residual value. The frequency of survey is dictated by the classification society with which the vessel is classed and in most cases has evolved over the years to be the best compromise between the cost of delaying a ship for survey and the risk of a defect becoming a hazard before it is discovered and repaired.

4 For a warship, political and operational considerations will dictate the life of a hull as there are no commercial pressures. The tendency is, therefore, for the life of warship hulls to be considerably longer on average than merchant ships. Most navies are chronically short of hulls to

fulfil their operational commitments and this problem can only get worse with the increasing complexity and cost of modern warships. Whatever the original intention of the requirements, laid down at the design stage of the ship, it is almost inevitable that a large proportion of hulls to that design will need to be pressed into longer than expected service with ever increasing cost of maintenance and risk of failure. It is therefore most important that the designer builds into the structure as many features as are possible within cost and other constraints which will allow the hull to continue in reliable service for as long as possible.

5 The two most significant phenomena causing deterioration of a steel structure in service are corrosion and fatigue. Some further discussion of corrosion and similar environmental attack for other materials is included in Chapter 5, while fatigue is covered in some detail in Chapter 13. In this chapter the practical aspects of design to minimise risk of loss of operational capability due to these phenomena will be discussed.

6 Corrosion will take place in a steel structure where it is inadequately protected against salt water (or other corrosive substances) either initially because protection was insufficient or incorrectly applied, or later because the protective coating has broken down and not been replaced. In either case the most likely reason is awkwardness of access which makes it difficult for the coating to be applied correctly in the first place and difficult for it to be surveyed and repaired. It is also made worse where the structure is such that salt water or condensation can lie without drainage, and where it may be hidden by decorative coverings.

7 The structural designer should, therefore, design structure which is easy to access for both the painter and surveyor, and should also ensure that adequate drainage is always arranged. It is especially important in tanks, bilges and similar double bottom structures that there is sufficient space for a man to get in and work with reasonable ease, and this requirement should be an *overriding constraint on the design* unless it is certain that the environment or material is such that deterioration cannot take place. It is equally important on a smaller scale that structural details are simple, without notches or sharp corners that are difficult to coat successfully. Additionally, notches are likely to constitute stress concentrations at which fatigue cracks can initiate. Regrettably, examples of notches abound in the majority of ship structures, for example holes with square corners from which cracks almost invariably grow. A right angle corner in a plane stress field is, after all, a singularity with theoretically infinite stress.

8 In relation to fatigue damage it is important to think about load paths when designing details. Fatigue will occur fastest where there is a high cyclic tensile stress range. In most large welded structures there are enough residual constraint stresses to ensure that even if the applied stress is compressive some part of the structure will always be in tension, and in a ship the most critical loads are due to the passage of waves and are therefore cyclic. A ship is therefore one of the worst structures for susceptibility to fatigue. The only recourse the designer has is to keep stress levels low and, in practical terms, that means minimising the number and severity of stress concentrations. If a load can be carried in-plane without having to be turned through an angle, then that is the best arrangement, for example a butt joint is better than a lap joint and a stiffener, deck or bulkhead should never be cranked without sideways support at the point where the structure changes direction, for example at the ends of deckhouses and around holes, but these are special cases and their designs should be analysed in detail to ensure that stresses are acceptable as described elsewhere in this book.

9 The foregoing paragraphs assume that the structure in its ideal state is adequate to withstand all expected operational loads for its agreed life. This itself is a question of probabilities and is dependent on the accuracy of the strength calculations, the assumptions on material properties and accuracy of construction and the probability of the design load conditions being exceeded. Most *design* is currently undertaken in a deterministic manner although some parameters may be calculated using probabilistic methods, in particular the design loads may assume some likelihood of exceedance in a given period of time as discussed in Chapter 3. Otherwise the uncertainties are intended to be covered in safety factors which may be explicit and obvious to the designer or implicit in the methods used. In any case it is essential that the designer does not approach a problem blindly but that margins are clearly examined and are shown to be appropriate to the requirement. Some mathematical procedures which can be of use in this area are discussed below (paragraph 13 et seq).

10 For a structure to be reliable in service it is especially important that it is properly surveyed and maintained. Whatever the cause of deterioration, be it poor design, poor preservation or unexpectedly severe usage, it is essential that any defects are discovered and repaired before they can constitute a hazard. Survey frequency and extent must therefore be based on the expected rate of structural deterioration and the reliability of repair procedures, and should also allow for uncertainty in the load, strength and other parameter assumed during design. Survey frequency should also probably increase as a ship ages. All these considerations are discussed in more detail in Chapter 16.

Practical Optimisation

11 Unlike reliability, the practical aspects of optimisation are not so readily presented. Mathematical optimisation requires the minimising or maximising of an 'object function' - weight, cost, reliability, etc - within a space containing constraints on the majority of the other parameters, and analytical techniques are discussed later (paragraph 24 et seq). During the design synthesis stage there will be insufficient data available for any form of numerical optimisation to take place (except insofar as local iterations are required to meet a specific design criterion), and indeed unless large gains are foreseen such calculations are rarely carried out even when the data is accessible. Additionally, it is unlikely that the constraints will be very precisely defined, for example the designer is likely to have to prepare a 'low cost' design, not perhaps a *minimum* cost, while not allowing weight to rise too high or sacrificing too much in reliability. It is difficult, if not impossible, to put numerical values on such 'fuzzy' parameters, although the techniques of mathematical manipulation of parameters which are defined using some form of weighting function are being developed. In practice it seems to be usually the case that costs and weights are not very sensitive to small changes in structural design assumptions, in other words minima or maxima are fairly flat, which relieves the designer of the need for precise optimisation. However, the corollary is that all the parameters have to be borne in mind simultaneously and the skill of the designer lies in developing the most acceptable compromise solution without numerical guidance. For more details of practical optimisation techniques see Caldwell (1986).

12 In this respect the structural designer must, as far as possible, take a long term view. It is no help to future users of the structure that reliability and safety were compromised to short term requirements for minimising cost or weight, as discussed by Chalmers (1986), unless indeed that minimisation is essential to the *function* of the structure, for example in high performance craft. If the minimisation is being pressed because only sufficient funds are available for a structure of limited utility, then the designer must argue professionally against such a design. If it still does ahead then it is essential that the limitations are properly documented and that the designer satisfies himself that adequate reliability is maintained through more frequent survey, and that the requirement for resources for the probable more frequent repair or early replacement is clearly stated. It is in this area that the link between optimisation and reliability is most apparent, and it means that in optimising the structure the design engineer has to ensure that all the constraints that are applied are consistent with his professional responsibilities.

Probabilistic Design and Analysis

13 An estimate of the reliability of a design can only be established through the use of probabilistic techniques, and there has been much activity in this field in recent years spurred on by advances in offshore structures, see, for example, Planeix (1986) and the Report of ISSC Committee IV.1, 'Design Philosophy' (1988). Indeed, only through the use of such techniques can a structural design by fully justified where there is very little in-service experience on a novel structural arrangement, for example tension-leg offshore platforms, or perhaps for SWATH (Small Waterplane Area Twin Hull) vessels.

14 The safety or reliability of a structure is the inverse of its failure probability, and so the calculation of reliability is the same as the establishment of the probability of failure. In this context failure must be defined in the form of a limit state and for ship structures there are two which apply:

Ultimate limit state	ULS
Serviceability limit state	SLS.

In either case it is necessary to postulate two exclusive sets of conditions in which the structure is either safe or has failed. For the ultimate limit state the failure condition will usually equate to the loss of the ship due to collapse of the hull girder; for the serviceability limit state the failure is likely to involve sufficient degradation of hull strength so that it cannot fulfil its intended purpose, or is no longer safe to continue operations and a return to port is essential if the ULS is not to be reached. A third failure state, known as the progressive limit stage (PLS), is sometimes defined relating to failure modes such as fatigue which are dependent on load history, but it is not a true independent limit state because actual failure only occurs when the SLS or ULS is reached.

15 The sets of conditions for the two limit states can be envisaged deterministically, except that for fatigue related failure it is difficult to write down the conditions due to the time history dependency. In fact, the theory for probabilistic treatment of fatigue life is very much in its infancy and is not yet useful to the designer (see ISSC Report IV.1 (1988) for the latest state of the

art). Otherwise, for the limit states in their simplest one dimensional form, safety can be defined as a measure of the difference or the ratio between the load S which is applied to the structure and the resistance R, in other words the safety margin M is equal to R-S or R/S. This is the simplest and traditional form of safety margin and is now known as the first level (of three) or first moment method because if the load and resistance are considered as stochastic variables only the mean (first moment) values are used. As long as M is greater than some value derived from experience then the structure is deemed to be safe, and the margin is then intended to cover the scatter in the distributions of R and S.

16 In terms of chronological sequence and third level or full probabilistic approach was the next to be investigated as described by Faulkner and Sadden (1979). That defines failure probability p_f as

(11.1)
$$p_f = \int_o^\infty \{F_R(x)\} f_S(x)dx$$

where f_S is the probability density function of the load and F_R is the distribution function of the strength in one dimensional space x. However, if it is considered that both the strength and the load include a number of components each with their own statistical distribution, that some of the components are dependent on others and that with a number of possible modes of failure the true failure space is multi-dimensional, the complexity of the solution to equation 11.1 will be appreciated. Further details for deriving p_f by third level methods may be found in Madsen et al (1986) where it is shown how such methods may be used - with considerable labour - to calibrate safety margins for less sophisticated techniques. Nevertheless, it is still possible to define a safety index ß which is analogous to the margin M and is a measure of the distance from the failure surface in multi- dimensional space (analogous also to the failure point for a single mode of failure) of a particular operational condition, as illustrated for a two dimensional space in *Figure 11.1*. This shows the expected design point ($E\{Z_1\}, E\{Z_2\}$) on the actual axes, known as Z space, in relation to a failure surface L_z which is then mapped onto new and more convenient axes, X space, such that $E\{X_i\} = 0$, that is the design point is at the origin, and the failure surface is L_x. For any point on the failure surface a safety index ß(x) is the distance from the origin, and the minimum safety index ß is the distance from the so-called design point x* which is found by minimising the distance between the origin and the approximate tangent plane to the failure surface. In addition to the description of the method by Madsen et al (1986), further references are included in the Report of ISSC Committee V.1 (1982).

17 In the ideal situation where the failure surface is defined in continuous algebraic terms the safety index may be calculated, although this clearly gets complex as the number of dimensions (number of failure modes) increases. In the real situation when the surface at best has discontinuous derivatives and may even itself be discontinuous, for example a sudden change in buckling mode in a grillage as load combinations vary, and when it can only be described numerically at a few discrete points, the problem of finding a meaningful value of safety index can be very difficult and can produce ambiguous results.

18 As a compromise which showed promise of possible solution for real engineering applications the second level or second moment method was developed, and originally presented

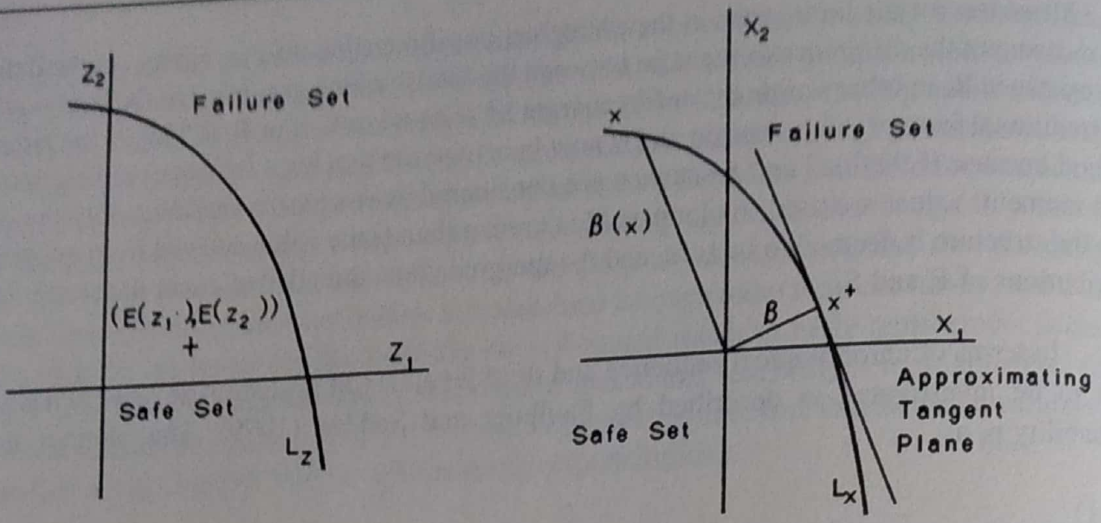

Figure 11.1 Geometric Illustration of the Safety Index ß

by Cornell (1969). In this method the safety index is defined in terms of the first and second moments of the distributions of load and strength, and in the special case of both being normally distributed can be calculated from

$$\beta = (\mu_R - \mu_S)/\sqrt{(\sigma_R^2 + \sigma_S^2)} \tag{11.2}$$

where μ and σ are the mean and standard deviation for the distributions of resistance and load indicated by the suffixes. Other expressions are available for other distributions and combinations of distributions, and provided the distributions are known the probability of failure is directly related to the value of ß as described by Madsen et al (1986). Faulkner and Sadden (1979) have used equation 11.2, together with a number of broad assumptions, to estimate the safety index for a number of merchant and warship designs and show that warship values of ß lie in the range 1 to 2, and merchant ships in the range 2 to 6, although these conclusions must be treated with some caution on account of the paucity of data on which they are based. However, there is no evidence from later publications to suggest that they are significantly wrong.

19 One of the problems of traditional methods of deterministic design is that it is never possible to be sure what margin exists between normal operation and a limit state, in other words how safe the structure is, because the statistical scatter in strength and load is not specified or even known. If, however, it was possible to define an acceptable value of ß, even if this could not be related numerically to a particular probability of failure, it would theoretically be possible to design ship structures to a consistent level of safety, at least for the ULS where a well defined failure mode exists. Referring back to Chapter 3 it will be noted that the extreme load can be defined in a form from which a mean value and a variance can be deduced. However, the ultimate strength derived in Chapter 7 remains deterministic and so the other parameters for equation 11.2 cannot yet be defined. The strength is, in fact, dependent on a large number of parameters some of which interact, for example weld distortion and residual stresses, and the effects of small variations in the parameters are mainly non-linear. Consequently, estimating the probability distribution for the strength is a complex problem, the solution of which is likely to need some form of Monte Carlo (random search) approach associated with the analysis methods discussed in

Chapter 7. Even when suitable values for the distributions are available it will still be necessary to analyse a number of existing ships to obtain current values of ß before a decision can be made on an acceptable value, in other words the method would still require calibration.

20 However, even though reliability methods are not yet developed to a state in which they are usable by a ship structural designer, very considerable work has been undertaken especially in relation to system analysis and its extension to offshore structures, where a number of research investigations have been completed, see for example the papers published in the Marine Structural Reliability Symposium by SNAME (1987). It is possible to deduce qualitative conclusions from this work which are of some help in the current context.

21 If the structure can be interpreted as a series system, for example a simple box beam or a simple truss, the overall system reliability is less than that of its most critical component if component failures are uncorrelated, and tend towards that of the most critical component if there is a strong correlation. Conversely, the reliability of parallel systems, for example multi-cellular box girders or trusses with many independent load paths, varies in an opposite manner, that is the overall reliability is better than the most critical component if there is no correlation and tends downwards as correlation increases. This type of response can be demonstrated using fault tree analysis for discrete components in clearly defined systems, but is difficult to apply to structures, where a fault tree can become rather convoluted. Nevertheless, the importance of structural redundancy is clear, especially if the strength of the parts of the structure are not strongly dependent on each other. More than one main strength deck, or a double bottom, are obvious examples where the reliability of the structure is increased well beyond the simple increase in static strength and, even for a structure with the same strength, multiple load paths will be more reliable than single paths.

22 For much simpler structures than the complete hull, attempts have been made to assess local reliability. For example, Hart et al (1986) have applied the second order method to the analysis of stiffened panels taking account of time variant loads. They have calculated values of mean and variance of local scantling dimensions and material properties from data available to Lloyd's Register of Shipping, as well as the mean and variance of the load for the panels as if they were part of the deck or bottom of a tanker. The derived safety index lies between about 1.5 and 4.5, depending on assumptions, which is consistent with the findings of Faulkner and Sadden (1979) reported above. However, the panels are treated in isolation from the remainder of the structure and no external interactions can be included so again the results must be treated with caution.

23 Summarising, interesting developments on reliability analysis of marine structures are being published with some frequency, mainly relating to offshore structures where novel arrangements are more common, where the loads for a particular location are more easily defined, where the consequences of failure may be more unacceptable and where funds for complex and unconventional analytical work may be more readily available. So far there is little which is of direct use to the ship structural *designer* although many of the results of other analyses confirm the desirability of including structural features which are well known subjectively to improve reliability. When adequate data is available to support reliability theory for surface ship hull structure it will still be necessary to calibrate it with existing successful designs before an acceptable safety standard can be specified. Nevertheless, specific studies may be justified for unusual or novel design configurations provided that suitable data can be derived from other equivalent engineering applications.

Optimisation

24 As suggested above in paragraph 11, the first problem is to define the criteria of optimisation, that is minimum weight, minimum first cost, minimum through life cost (or maximum return), maximum space, or perhaps maximum reliability. These parameters will generally be mutually exclusive. Also it is necessary to remember that the optimum from the view of the user or owner (for example, minimum life cycle costs) may be different from that of the shipbuilder (maximum profits). A further problem is that an optimum for the structure is not necessarily an optimum for the whole ship; all systems, including structure as a system, should really be optimised together, although this would be a mammoth task even if data and techniques were available. Furthermore, any change in rôle during the ship's life is likely to invalidate any over refined optimisation.

25 However, in general structure does not interact strongly with other ship systems, so it is not unreasonable to start by optimising structure separately and then checking that the optimised structure does not impose too tight constraints on other systems. To take an extreme example, an optimised bulkhead spacing for structural weight may not be suitable for damage stability but could be a good starting point. The criterion for optimisation will be minimum weight in weight sensitive designs and, otherwise, minimum cost, although this is rarely clearly defined especially in relation to the difference between construction cost and through life cost. However, the techniques used are general and independent of criteria. For further information on cost optimisation see Hughes (1983), Kuo et al (1983) and Winkle and Baird (1986).

26 The criterion being optimised is known mathematically as the 'object function' and knowledge of the sensitivity of the object function to changes in design variables is as important as knowing the optimum. This is because at some stage a compromise will have to be reached and changes can then be made to variables having least effect on the optimum; also insensitive criteria will need less design effort. Sensitivity to constraints (for example, minimum required strength) can also be useful to know, as it may be possible to ease constraints slightly if large improvements in the optimum of the object function can then be made.

27 The specification of the criteria and constraints will be considered in a little more detail later, but it is worth first looking at available optimisation techniques. The optimisation task reduces to forms of linear and non-linear mathematical programming, and it is first necessary to define the problem in mathematical terms. The object function is

$$f(x) = F(x_1, x_2, \ldots\ldots\ldots, x_n) \qquad (11.3)$$

where n is the number of design variables (scantlings, layout etc). The constraints are also defined as

(11.4a) $$h_{ij}\,(x_1,\,\ldots\ldots,\,x_n,\,\sigma_1,\,\ldots\ldots,\,\sigma_m) = 0$$

(11.4b) $$g_{ij}\,(x_1,\,\ldots\ldots,\,x_n,\,\sigma_1,\,\ldots\ldots,\,\sigma_m) = 0$$

where h_{ij} represents equilibrium and compatibility (boundary conditions), g_{ij} represents design limitations, x_i are the design variables and σ_j are the behaviour variables (stresses etc). The problem then reduces to a search of an n dimensional space for a minimum (or maximum) value of F(x), which at the same time lies in the volume bounded by the constraint equations. *Figure 11.2* gives a two dimensional representation of the problem.

28 If the object function and its constraints are linear, then it is called a linear programming problem and standard mathematical methods and computer programs are available, see for example Farkas (1984) for more details and references. Unfortunately, however, it is rare to find any of the equations to be linear and so non-linear programming methods are necessary. The general solution involves continuing cycles of analysis and redesign. An initial design point is selected (usually an acceptable design) and successive modifications are carried out to the object function within the n dimensional space until the optimum is arrived at. This process is called a search pattern and the major problem is formulating an optimisation method is development of an acceptable search pattern which finds a true global optimum (and not a local one), in reasonable time.

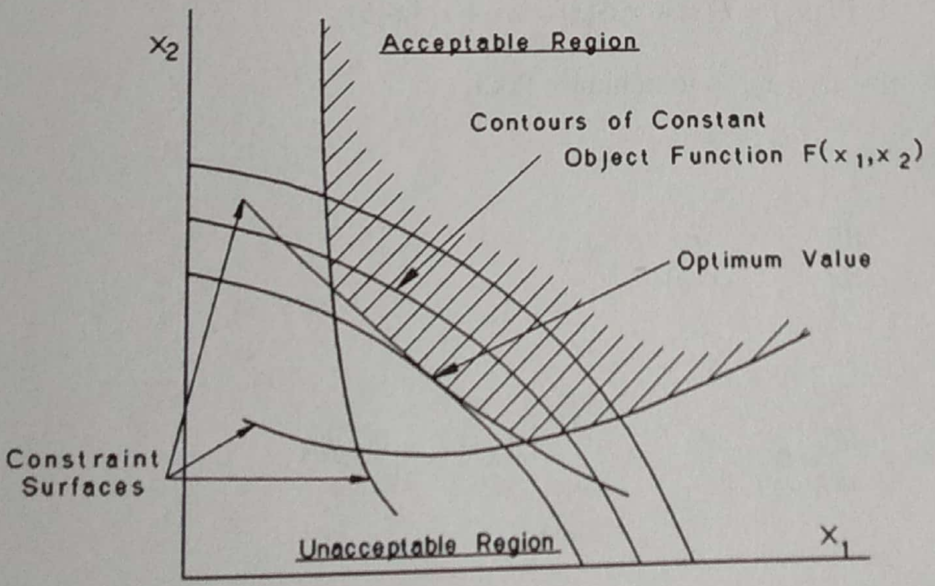

Figure 11.2 Representation of Optimisation

29 Perhaps the most common method is the Sequential Unconstrained Minimisation Technique (SUMT), which converts a constrained optimisation problem into an unconstrained one and is summarised by Farkas (1984) and presented in detail by Fiacco and McCormick (1968). The conversion requires a modified object function P(x,r) defined as

(11.5) $$P(x,r) = F(x) + rG(x)$$

where r is a scalar factor and G(x) is a penalty function of the form

(11.6) $$G(x) = \sum_{i=1}^{n} \sum_{j=1}^{m} (1/h_{ij} + 1/g_{ij})$$

such that as either h_{ij} or g_{ij} tend to zero, G(x) tends to infinity. P(x,r) is optimised repeatedly for a sequence of r decreasing to zero. If the optimum value of P(x,r) for finite r is $P^*(x,r)$ and the corresponding value of x is $x^*(r)$, then as $r \to 0$, $P^*(x,r) \to F^*(x)$ and $x^*(r) \to x^*$, where $F^*(x)$ and* represent the optimum value of F(x) and its coordinate x.

30 This method has the advantage of being easily programmed for computer in addition to there being more mathematical methods for unconstrained optimisation available. However, it must be noted that there will be as many times more analyses to be carried out as there are steps in r and so obtaining convergence may be expensive and time consuming. The method is probably best applied to small and medium sized problems and examples are presented by Farkas (1984). It can be illustrated by a simple one dimensional problem where it is required to minimise the function F(x) = ax subject to the constraint g(x) = x–b > 0 as shown in *Figure 11.3*. Hence

(11.7) $$P(x,r_k) = F(x) + r_k G(x) = ax + r_k/(x-b)$$

where $r_1 > r_2 > r_3 \ldots\ldots > r_k$, so to minimise $P(x,r_k)$

the derivative

(11.8) $$\frac{dP}{dx} = a - \frac{r_k}{(x-b)^2}$$

so that when

(11.9) $$\frac{dP}{dx} = 0 \qquad x_{\min} = b + \sqrt{(r_k/a)}$$

and

(11.10) $$P(x_{\min}, r_k) = ab + 2\sqrt{(ar_k)}$$

hence as $r_k \to 0$, the limiting values are $x^* = b$ and $F^*(x) = ab$ which can be seen by inspection of Figure 11.3 to be the minimum value of F(x).

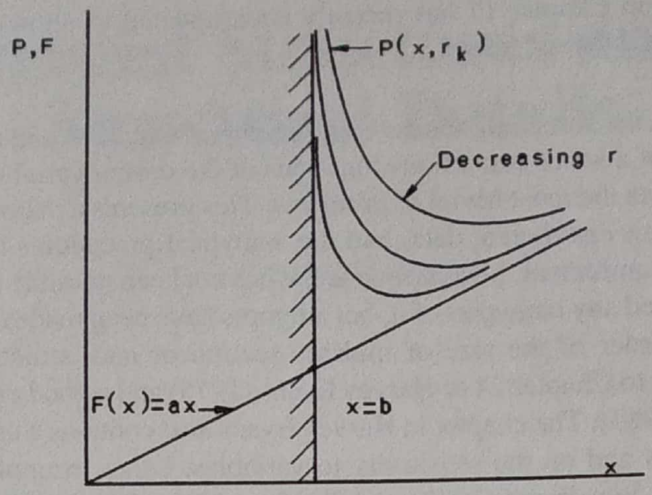

Figure 11.3 Illustration of SUMT Technique

31 As the problem size increases the analysis part of the calculation becomes much more time consuming than the optimisation process and so the number of iterations must be kept to a minimum. In this context direct search methods have been developed aimed at requiring re-analysis only after much effort has been expended in ensuring that it is worthwhile. The largest class of direct search methods is called the method of feasible directions when, in the step by step approach, step length and direction are chosen so as to lie inside the acceptable domain. Few search algorithms are available but some are described by Zoutendijk (1960). This method lends itself particularly to use in conjunction with finite element methods of analysis, when the object functions and constraints may be defined in terms of the finite element structural parameters.

32 There is an extensive library of search patterns available for both constrained and unconstrained problems. Basically all search patterns can be divided into two classes, those that require computation of first derivatives and those that do not. The first class is called the gradient technique and uses the first derivative of the object or modified object function to direct the search. The second class is called pattern search and directs the search according to the success of previous sets of moves. Gradient searches usually converge quicker but the computation of the derivative generally takes longer.

33 A different class of search pattern altogether is the random search pattern which involves some sort of random sequence in the selection of design parameters. This approach is desirable within non-convex constraint surfaces (where continuous search patterns may have difficulty in finding a true optimum) but may involve many re-analyses to achieve an acceptable probability of optimisation and is in consequence a very inefficient method.

34 A great disadvantage of most optimisation techniques is that they cannot handle discrete or discontinuous variables, for example discrete plate thicknesses and stiffener sizes. Methods do exist but are not sufficiently well developed for more than the simplest of structural application, and examples are presented by Farkas (1984). However, the program MAESTRO due to Hughes

(1983) and discussed in Chapter 17 has recently been updated to allow the optimisation of a structure with discrete scantling sizes.

35 It is clear from the foregoing discussion that object functions and constraints need to be specified in the form of a set of continuous functions of the design variables for a solution to be achievable for more than the most trivial of problems. This presents a major difficulty in practical applications as there are insufficient data, and the analytical procedures in general do not lend themselves to such a requirement. In consequence, it has not been possible to optimise a complete ship's structure or indeed any large part of it, but attempts have been made to treat smaller parts of the structure, of the order of the size of midship-section or tank structure. Some details are contained in references to Chapter 24 of Harvey Evans (1975) and a good example is presented by Evans and Khoushy (1963). The chapter in Harvey Evans also contains a useful discussion on the estimation of functions and on the sensitivity to variables. Other examples and discussion are given by Caldwell and Woodhead (1973) and Smith and Woodhead (1974).

Choice of Object Function

36 Because weight is simpler to define in terms of design variables it has been the main object of research to date. Clearly in weight limited designs, such as aircraft, hydrofoils or surface effect ships, structural weight has economic rewards. For displacement vessels, reduced weight and consequently reduced scantlings will only have the advantage (other than the obvious one of less material cost) of increased space and payload, and possibly better stability. There will be accompanying disadvantages of greater risk of failure from corrosion together with a greater maintenance load, as discussed by Skaar et al (1987).

37 Construction cost, although loosely quoted in cost/tonne, is not necessarily reduced by minimising weight. The cost/tonne varies with ship type and size and includes factors for labour and overheads, which themselves are bound up with complexity, inspection requirements, quality assurance and other parameters as discussed by Chalmers (1986). The cost/tonne figure is therefore meaningless as a function for optimisation and is only of use in estimating costs of similar ships.

38 Reductions in building costs may be possible by using cheap materials, standard structural arrangements and minimum inspection. What data there is available tends to be inconsistent, possibly due to different shipbuilders using different accounting procedures, and so it is very difficult to produce any reasonable sort of object function, although attempts have been made in particular cases, for example Moe and Lund (1968) and more recently Winkle and Baird (1986).

39 In relation to the whole ship, a minimum through life cost is probably the most desirable object function, though not often pursued due to economic constraints on construction cost. It is, however, very difficult to quantify and any numerical optimisation using this function is unlikely to be achieved for some time.